# An Energy Analysis of the Catalytic Combustion Burner

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**Abstract:** The gas boilers of conventional flame always produce varying degrees of combustion products NOx and CO, which pollute the environment and waste energy. As a new way of combustion, catalytic combustion breaks the flammable limits of conventional flame combustion, and realizes the combustion of ultra-natural gas/air mixture under the flammable limits. Its combustion efficiency is higher, which improves the ratio of energy utilization. Applying the catalytic combustion to gas boilers could solve the gas boilers' lower combustion efficiency, and achieve energy savings. On the basis of the catalytic combustion burner, the catalytic combustion burner was designed according to the catalytic combustion and water heaters. In this paper, we analyzed the heat loss and thermal efficiency of the catalytic combustion burner, and compared it to that of flame combustion boilers. The results showed that catalytic combustion burner □'s heat loss is not so high as originally considered, and its pollutant emissions are lower.

**Key words:** catalytic combustion, flame combustion, heat loss, energy saving, near-zero pollutant emission

## 1. INTRODUCTION

In order to satisfy indoor comfortable condition, the buildings of northern areas need to be heated in winter, so the large and small heating boilers come into running which brings about the degradation of air quality and energy shortage in heating season. The public have been aware of the environmental pollution caused by coal boilers, and some areas have changed partial coal boilers into gas or oil boilers. But none of the areas changed the flame combustion way of conventional boilers. In deed, the flame combustion way has its own disadvantages. In the way of flame combustion, the combustion temperature is always above 1800K, however, the production rate of NOx will increase rapidly with temperature beyond 1500K [1]. The gas boilers burn clean energy-natural gas, but they will also produce many NOx pollutants. In addition, the combustion efficiency of flame is lower, which brings the energy waste. With the increasing of energy saving and environmental protection, it is necessary to change the flame combustion way of gas boilers.

As a new way of combustion, the catalytic combustion reduces the light-off temperature, and deepens the oxidation extent as well as improves the reactant conversion, in the process of catalytic reaction. Meanwhile, it controls the production of the thermal reaction NOx by weakening the combustion peak value [2]. So the conversion of natural gas and combustion efficiency in catalytic combustion are higher, and the concentration of pollutants is lower.

The catalytic combustion's applications can be found in a number of domestic (Ro et al., 1997) and industrial process heaters (Seo et al., 1999; Griffin and Wood, 2001) in the outland [3]. In our country, the applications of catalytic combustion will also be an irresistible tendency. And the application of catalytic combustion to gas boilers will improve the combustion efficiency, and reduce NOx emission.

## 2. EXPERIMENTAL SET-UP

The experiments were carried out in catalytic combustion burner□, 450*200*700mm. And it is a water heater, consisting of catalytic reactor (2.4cm$^2$) and heat exchanger. The reactor used honeycomb catalytic monolith, which is coated with catalyst Pt.

Catalytic combustion burner □ is a cylindrical burner, and its height is 100mm and sectional diameter is 100mm. Compared with burner□, burner □alleviates the impact of mixture flow on the catalyst by improving the injector, and has the water heater's structure by connecting with the water system.

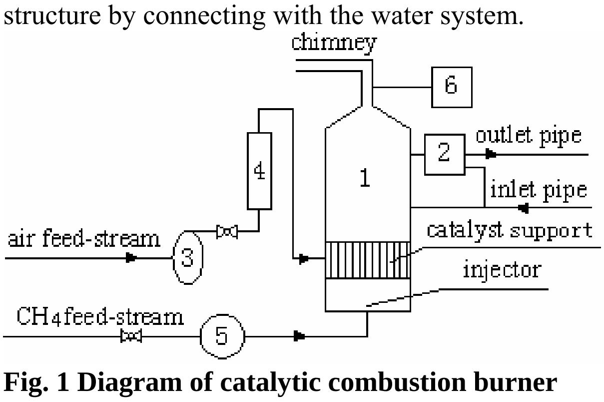


**Fig. 1 Diagram of catalytic combustion burner**

1-Burner 2-Calorimeter 3-Fan
4-Rotameter 5-Wet gas meter
6-Gas analysis meter

The reactant gas feeds of natural gas and air were regulated via wet gas meter and LZB-15 glass rotameter, 4-1200 l/h and 0-16 m$^3$/h of full-scale range, respectively. The parameters of water were measured via calorimeter, while the dry gas product

**Tab. 1 Compositions of natural gas**

| Compositions | $CH_4$ | $C_2H_6$ | $C_3H_8$ | i-$C_4H_{10}$ | n-$C_4H_{10}$ | $CO_2$ | $N_2$ | $O_2$ |
|---|---|---|---|---|---|---|---|---|
| Volume fraction (%) | 93.908 | 0.951 | 0.198 | 0.012 | 0.011 | 2.657 | 1.894 | 0.369 |
| Lower heating value (kJ $Nm^{-3}$) | 35906 | 64397 | 93244 | 122857 | 123649 | 0 | 0 | 0 |
| Theoretical air ($Nm^3$ $Nm^{-3}$) | 9.137 | | | | | | | |
| Average lower heating value (MJ $m^{-3}$) | 34.54 | | | | | | | |

flow of catalytic combustion was analyzed via the MIS gas analysis meter. Fig. 1 shows the diagram of the experiments (The broken line connected to the calorimeter is the data line of inlet water).

Table 1 shows the compositions of natural gas obtained via gas chromatograph.

## 3. HEAT LOSS CALCULATIONS

For gas boilers, heat balance equation [4] is given by:

$$Q_r = Q_1 + Q_2 + Q_3 + Q_5$$

where $Q_r$ (in kJ $m^{-3}$) is the lower heating value of natural gas injected into the boiler, $Q_1$ (in kJ $m^{-3}$) is the available heat of the boiler, $Q_2$ (in kJ $m^{-3}$) is the waste heat loss, $Q_3$ (in kJ $m^{-3}$) is the heat loss of incomplete combustion for gas, and $Q_5$ (in kJ $m^{-3}$) is the external heat loss.

### 3.1 Combustion Efficiency

In the experiments, the exhaust parameters consisting of pollutant concentrations of CO and NO and exhaust temperatures, were obtained via the gas analysis meter at the inlet of chimney. The concentrations of CO and NO reflect the pollutant emissions of catalytic combustion burner□, and the exhaust temperature reflects the waste heat loss.

Table 2 shows the exhaust parameters for 5% of the gas/mixture ratio at five velocities of natural gas flow rate varying between $1.00\times10^{-4}$ and $1.67\times10^{-4}$ $m^3$ $s^{-1}$, i.e. at five power inputs varying between 3.45 and 5.76kw. The gas/mixture ratio is defined by the percentage of gas in natural gas/air mixtures.

**Tab. 2 The exhaust parameters for catalytic combustion burner Ⅱ**

| Natural gas flow rate$\times10^4$ ($m^3$ $s^{-1}$) | Power input (kw) | NO (ppm) | CO (ppm) | $SO_2$ (ppm) | Exhaust temperature (℃) |
|---|---|---|---|---|---|
| 1.00 | 3.45 | 3 | 1 | 1 | 73 |
| 1.17 | 4.03 | 2 | 1 | 1 | 90 |
| 1.33 | 4.61 | 2 | 0 | 2 | 93 |
| 1.50 | 5.18 | 0 | 0 | 2 | 106 |
| 1.67 | 5.76 | 0 | 0 | 4 | 114 |

In the way of flame combustion, the combustion efficiency of gas boilers is 99%~99.5% in better burning conditions, so $q_3$ ($Q_3 / Q_r$) of flame burners is always between 0.5% and 1.0% [7]. However, the catalytic combustion burner □ can achieve the complete combustion of natural gas in the catalytic combustion way, and the combustion efficiency is very high and can reach 99.9%[5]. So $q_3$ of catalytic combustion burner□ is considered to equal 0.1%, which is lower 0.4~0.9% than flame boilers.

Considering the results of table 2, the concentrations of combustion products NO and CO are 3 and 1ppm in the experiments, respectively, which are consistent with those measured by MA. So catalytic combustion burner□ is considered to achieve the near-zero pollutant emissions.

### 3.2 Combustion Characteristics

Due to the oxygen-enriched combustion way of catalytic combustion burner □, the excess air coefficients and volume fractions of each combustion product are quite different from those of conventional gas burners. So, in order to gain the waste heat loss of catalytic combustion burner □, the excess air coefficients and volume fractions should be calculated firstly.

In table 3, the excess air coefficients were calculated for different gas/mixture ratios according to the definitions.

**Tab. 3 The excess air coefficients for different gas/mixture ratios**

| Gas/mixture ratio (%) | Actual air ($Nm^3$ $Nm^{-3}$) | Theoretical air ($Nm^3$ $Nm^{-3}$) | Excess air coefficient |
|---|---|---|---|
| 5.0 | 19.0 | 9.137 | 2.08 |
| 5.5 | 17.2 | 9.137 | 1.88 |
| 6.0 | 15.7 | 9.137 | 1.71 |
| 6.5 | 14.4 | 9.137 | 1.57 |

According to table 1 and chemical equations of each composition for 1$m^3$ of natural gas, the compositions of combustion products could be obtained for different gas/mixture ratios. Table 4 shows the compositions for the very lean mixture of 5%, i.e. the maximum excess air coefficient $\alpha = 2.08$.

From table 4, we could find that the $O_2$ volume fraction in the exhaust for catalytic combustion burner □ is about 10%, however that for flame combustion burners is about 2~4%. It is much higher than that for flame combustion burners, due to the oxygen-enriched combustion way in catalytic combustion burner□.

### 3.3 Waste Heat Loss

Because the carbon loss for gas boilers equals 0, the expression of waste heat loss for gas boilers is [4]:

**Tab. 4 Combustion characteristics of natural gas at α =2.08**

| Name | Units | The expressions | Results |
|---|---|---|---|
| Theoretical air | Nm$^3$ Nm$^{-3}$ | $\frac{1}{21}\left(0.5H_2+0.5CO+\sum(m+\frac{n}{4})C_mH_n+1.5H_2S-O_2\right)$ | 9.137 |
| Gas/mixture ratio | % | Given | 5.0 |
| Excess air coefficient | | Table 3 | 2.08 |
| Actual $H_2O$ volume | Nm$^3$ Nm$^{-3}$ | $0.01\left(H_2+H_2S+\sum\frac{n}{2}C_mH_n+124d_g\right)+0.0161\alpha V^0$ | 2.222 |
| Actual $N_2$ volume | Nm$^3$ Nm$^{-3}$ | $0.79\alpha V^0+N_2$ | 15.029 |
| Actual $O_2$ volume | Nm$^3$ Nm$^{-3}$ | $0.21(\alpha-1)V^0$ | 2.071 |
| Actual $RO_2$ volume | Nm$^3$ Nm$^{-3}$ | $0.01\left(CO+CO_2+\sum mC_mH_n+H_2S\right)$ | 0.992 |
| Actual exhaust volume | Nm$^3$ Nm$^{-3}$ | $V_{RO_2}+V_{N_2}+V_{H_2O}+V_{O_2}$ | 20.313 |
| $N_2$ Volume fraction | % | $V_{N_2}/V_y$ | 73.987 |
| $O_2$ Volume fraction | % | $V_{O_2}/V_y$ | 10.195 |
| $RO_2$ Volume fraction | % | $V_{RO_2}/V_y$ | 4.881 |
| $H_2O$ Volume fraction | % | $V_{H_2O}/V_y$ | 10.937 |

$$q_2=\frac{Q_2}{Q_r}\times 100=\frac{(I_{py}-\alpha_{py}I^0_{lk})}{Q_r}\times 100\ \% \qquad (1)$$

where $I_{py}$ (kJ m$^{-3}$) is the enthalpy of waste for 1m$^3$ of natural gas, $\alpha_{py}$ is the excess air coefficient, $I^0_{lk}$ (kJ m$^{-3}$) is the enthalpy of theoretical air at the inlet temperature, for 1m$^3$ of natural gas, and the other parameters are the same as above. And for catalytic combustion burner □, the expression (1) of waste heat loss is also logical.

Based on table 4 and temperature-enthalpy table [4], the expression of enthalpy and exhaust temperature for 1m$^3$ of natural gas , between100 and 200□, is obtained with interpolation method:

$$I_{py}=27.57t-25 \text{ kJ m}^{-3}\ (t=100\sim200\ □) \qquad (2)$$

From the appendix□-9 of reference [6], we can obtain the polynomial expression for calculating the average heat capacity of air. However, considering that the inlet air temperatures are always between 30 and 100□, we can skip the higher-order infinitesimal, and the heat capacity of air is a constant:

$$c=A=1.3196457 \quad \text{kJ Nm}^{-3}\ □^{-1}$$

In the experiments, the inlet air temperature is 30□, so the enthalpy of theoretical air for 1m$^3$ of natural gas is:

$$I^0_{lk}=V_0ct=356 \quad \text{kJ m}^{-3}$$

Based on the expressions of $I_{py}$ and $I^0_{lk}$, the expression of waste heat loss is yielded for the very lean mixture of 5%:

$$q_2=\frac{27.57*t-765}{345.4}\ \%\ (t=100\sim200\ □) \qquad (3)$$

However, the maximum exhaust temperature is 114□, as shown in table 2. At 114□, the waste heat loss of catalytic combustion burner□ is 6.88%, derived from expression (3).

# 4. ENERGY SAVING ANALYSIS

In order to find the influence degree of oxygen-enriched combustion way on it, the waste heat loss in catalytic combustion burner □ is compared with that of flame combustion burners. And the waste heat loss of flame combustion burners is calculated below.

Similar to the derivations of expression (2) and (3) for catalytic combustion burner□, the following expressions for flame combustion burners are obtained, for 1.2 of excess air coefficient:

$$I_{py}=16.86t-22 \text{ kJ m}^{-3}\ (t=100\sim200\ □) \qquad (4)$$

$$q_2=\frac{16.86*t-449}{345.4}\ \%\ (t=100\sim200\ □) \qquad (5)$$

At the same exhaust temperature $t_{py}=114$ □, the waste heat loss of flame combustion burners is 4.26%, derived from expression (5), which is lower than that of catalytic combustion burners. Compared 6.88% with 4.26%, it was concluded that the oxygen-enriched combustion way in catalytic combustion burner □ increased about 50% of the waste heat loss.

But for conventional gas boilers without condensers, the exhaust temperature is usually much higher than 114□.At the exhaust temperature $t_{py}=180$ □, the solution of expression (3) is 7.49%. Compared with 6.88%, it could be concluded that the oxygen-enriched combustion way of catalytic combustion burner is still lower than that of flame combustion burners at $t_{py}=180$ □, for 1.2 of excess air coefficient.

The oxygen-enriched combustion way for catalytic combustion burner increases the excess air coefficient to 2.08, but the waste heat loss is not so also duo to the oxygen-enriched combustion way. In the catalytic combustion way, the plate surface temperature is lower than the flame temperature in flame combustion way, and the maximum wavelength of radiation ray (i.e. the wavelength of the maximum homogeneous radiation) is 4~6μm, which is in the range of infrared, so the most reaction heat is radiated by infrared [8]. Then, the most heat transfer in catalytic combustion burner is radiation, which improves the energy utilization ratio and decreases the exhaust temperature and waste heat loss.

For conventional flame combustion, the radiation of its own is lower, and the most radiation depends on the waste or carbon granules. However, gas boilers burn the clean energy-natural gas, whose exhaust gas has a small of the carbon granules. Duo to the above reason, the convection heat transfer is the main way of heat transfers in conventional gas boilers and the waste heat loss is higher relatively.

## 5. CONCLUSIONS

In the light of the above calculations and analyses, the following conclusions can be obtained for catalytic combustion burner□:

(□)The combustion efficiency is higher 0.4~0.9% than that of flame combustion burners, so $q_3$ is lower 0.4~0.9% relatively;

(□) The waste heat loss of catalytic combustion burner □ is higher than that of flame combustion burners at the same exhaust temperature;

(□) For the maximum excess air coefficient of $\alpha = 2.08$ , at the highest exhaust temperature of $t_{py} = 114$ □, the waste heat loss is 6.88%, which is lower than 7.49%, the waste heat loss of flame combustion burners for $\alpha = 1.2$, at $t_{py} = 180$ □;

(□) The CO and NOx pollutants in the waste are much lower than that of flame burners, and the catalytic combustion burner □ achieves near-zero pollutant emissions.

The catalytic combustion burner □ is a new combustion equipment, and can solve the shortcomings of conventional flame combustion burners. It has the adventures of higher combustion efficiency and thermal efficiency, and achieves the near-zero pollutant emission. In the future, the catalytic combustion way will be applied to conventional gas boilers and realize heating in winter.

high as considered via the above calculations. This is

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